PARAMETRIC STUDY OF SCARF ADHESIVE JOINTS UNDER TENSILE LOADING A COMPARATIVE STUDY OF ANALYTICAL, EXPERIMENTAL AND FINITE ELEMENT RESULTS

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Abstract

Adhesive bonding is a promising alternative to mechanically fastened joints since it allows for load transfer over a continuous interface and eliminates holes which can act as stress raisers. In the present work, a scarf bonded joint is studied under static tensile loading. The parameters investigated are the scarf angle, adhesive layer thickness and resin to hardener mixture ratio. Stainless-steel adherends and an epoxy adhesive were used in the source study. The source study combined a Taguchi L9 experimental design with finite element analysis (FEA) and compared numerical predictions with experimental results. The maximum response reported was 2.3808 N/mm2 for a 60° scarf angle, 1 mm adhesive layer and 1:1 mixture ratio. For a representative comparison, the report gives equivalent stress values of 40.86 MPa by mathematical calculation and 42.372 MPa by FEA for a riveted joint, compared with 2.29 MPa analytically, 2.38 MPa by FEA and 2.34 MPa experimentally for the adhesive joint. These values show a much lower recorded stress response of the investigated bonded configuration. However, the dataset is limited to a small number of factor combinations, and the response wording and units reported need to be clarified prior to publication. The paper therefore presents the results as a preliminary parametric investigation and not as a general design rule.

Index Terms—Adhesive bonding, epoxy adhesive, finite element analysis, joint strength, scarf joint, tensile loading, Taguchi method.

I INTRODUCTION

Joining methods lie at the heart of the design and manufacture of load bearing structures. Bolting, riveting and welding are still in common use, but holes, local contact and geometric discontinuities can lead to stress concentrations. Adhesive bonding spreads the load across a

bonded area, and can join dissimilar materials without drilling fastener holes. Reviews of bonded composite structures have identified joint geometry, surface preparation, adhesive properties and environmental conditions as important influences on performance [1]. However, such advantages do not remove the necessity for careful design. Bonded joints can fail at the adhesive-adhered interface or within the adhesive, and the local edge stresses may control crack initiation. A scarf joint is made by joining inclined surfaces together. If the adhesive layer is under axial tension, it experiences normal and shear stresses. Its strength can be affected by scarf angle, bond-line thickness, surface condition, adhesive formulation and adhered properties. Studies on scarf joints have shown that the stress distributions at the interface and strength predictions can be dependent on the scarf angle and adhesive thickness, and simple stress-based criteria may not be enough to predict the failure in dissimilar-material joints [2], [3].This paper summarises the provided Stage II report into an IEEE-style technical paper. It is concerned with the reported parametric study and comparison of analytical, FEA and experimental outputs. The work must be read keeping in mind the limitations of the source data, missing test details have not been invented.

II. RELATED WORK

Banea and da Silva have reviewed adhesive joints in composite structures and discussed the importance of surface preparation, joint configuration, properties of the adhesive, environmental effects and numerical failure prediction [1]. Their review points out that there is no single failure criterion which can be applied to all joint configurations and material combinations.Afendi et al. [5] investigated the uniaxial tensile loading of epoxy bonded dissimilar adherends scarf joints. In their study scarf angles and bond-line thicknesses were considered and they reported stress concentrations near the interface corner to be important in interpreting failure [2]. He et al . studied the stress distributions of a scarf joint under static tensile load by three-dimensional finite element calculation and experiment, and discussed the discrepancies between the two- and three-dimensional predictions and the significance of interface-edge stresses [3].Other studies have explored the effect of surface roughness, adhesive thickness and overlap geometry on the strength of joints [4], and the influence of the overlap length on the performance of single-lap joints [5]. To summarise, these studies indicate that adhesive strength cannot be considered as a material property per se, but that joint geometry and adhesive-layer parameters should be considered together.

III. OBJECTIVES AND SCOPE

The objective is to investigate the influence of scarf angle, adhesive-layer thickness and epoxy resin to hardener ratio on the obtained response of a scarf adhesive joint under static tensile loading. The work compares a riveted joint with a scarf bonded joint and uses analytical calculations, FEA and experimental measurements as complementary approaches. The parameters considered were scarf angles of 30°, 45°, and 60°, adhesive layer thicknesses of 0.5, 1.0, and 1.5 mm, and mixture ratios of 1:1, 1.5:1, and 2:1 as given in the source report.

IV. MATERIALS AND METHOD

A Material and Specimen PreparationThe source report states the adherend material was SS 304 stainless steel and the bonding material was a two-part Araldite epoxy adhesive. The specimen preparation was degreasing, abrasion, cleaning with acetone, adhesive application, scarf face alignment and curing. The report describes a tensile-loading investigation and mentions the use of a universal testing machine. The source has contradictory descriptions of the adhesive product and curing times in various sections. The precise product grade and final curing protocol should be verified against laboratory records prior to submission.

B. Experimental SetupNumber of factor combinations was reduced using Taguchi L9 orthogonal array. The three factors were the angle of the scarf (30°, 45°, 60°), bond-line thickness (0.5, 1.0, 1.5 mm), and the ratio of resin to hardener (1:1, 1.5:1, 2:1). Table I shows the nine combinations and the response values reproduced from the source report. The reported dataset is taken at face value. No further trials or tests of statistical significance are assumed.

C. Analytic and Numerical EvaluationThe source report presents analytical stress relations for a scarf joint under axial loading and finite element results obtained from ANSYS. The model compares stress fields for certain combinations of factors. In scarf joints, the axial stress decomposes into a normal and a shear component relative to the inclined bond plane, and the scarf angle alters the state of stress in the adhesive. A comparison of a typical riveted-joint calculation, a bonded-joint calculation and experiment is also presented.

V. RESULTS AND DISCUSSION

Taguchi L 9 out comes The nine response values of the source document are reproduced in Table I. In the table the source labels these values as breaking strength in N/mm², while parts of the discussion refer to them as maximum von Mises stress in MPa. N/mm² and MPa are

numerically equivalent units, but "breaking strength" and "von Mises stress" are not equivalent response definitions.

Run	Scarf angle (°)	Layer thickness (mm)	Resin:hardener	Reported response (N/mm²)
1	30	0.5	1:1	0.1102
2	30	1.0	1.5:1	0.2075
3	30	1.5	2:1	0.3308
4	45	1.0	2:1	0.3906
5	45	1.5	1:1	1.5624
6	45	0.5	1.5:1	1.1718
7	60	1.5	1.5:1	0.8928
8	60	0.5	2:1	1.5475
9	60	1.0	1:1	2.3808

The maximum value reported in the array of nine runs was 2.3808 N/mm2 at a 60° scarf angle, 1.0 mm bond-line thickness and 1:1 ratio of resin-to-hardener. The lowest value reported is 0.1102 N/mm2 at 30°, 0.5 mm and 1:1. These results show that the response is significantly different between the combinations tested. However, the array itself does not demonstrate statistical significance or that the same combination is optimal beyond the levels tested. Each combination appears once and no replicate variability or estimates of uncertainty are presented.

B. Comparison of analytical, FEA and experimental results Joint/method Reported

Joint / method	Reported equivalent stress (MPa)	Interpretation
Riveted joint—analytical calculation	40.86	Source-reported comparison
Riveted joint—FEA	42.372	Source-reported comparison
Scarf adhesive joint—analytical calculation	2.29	Source-reported comparison
Scarf adhesive joint—FEA	2.38	Source-reported comparison
Scarf adhesive joint—experiment	2.34	Source-reported comparison

The source report gives close values for the adhesive joint comparison: 2.29 MPa analytically, 2.38 MPa by FEA and 2.34 MPa experimentally. The experimental value is about 1.7% different from the FEA value as calculated relative to the FEA result. This numerical similarity is encouraging but should not be considered a complete validation, as the

report does not contain repeated measurements, uncertainty bounds, a mesh-convergence study, or a fully specified material model. The stresses reported for riveted joints are considerably higher than those reported for bonded joints in the comparison considered. One explanation for the design could be that the bonded configuration avoids fastener holes and the associated geometric discontinuities. However, a fair engineering comparison requires that both models use the same load, specimen dimensions, boundary conditions and comparable stress definitions. The results should be taken as evidence for the configuration investigated and not as proof that adhesive joints always give lower stress or are always stronger than riveted joint C. Influence of scarf angle and other factors. The source study found that the most influential factor out of all the factors investigated, was the scarf angle, with the highest response reported at 60°. This is consistent with the source data set, in which the largest single response occurs at 60 ° with a 1.0 mm layer and a 1:1 mixture. However, the nine-run table does not allow to isolate the contribution of each factor independently and the reported values are not accompanied with a full signal-to-noise analysis or ANOVA table. Thus, the ranking of influence presented in this manuscript should be reported as the conclusion of the original study and not as a statistically verified result. Reported response is also seen to be affected by bond-line thickness and mixture ratio. The trend is not monotonic for all combinations; factor interactions or differences in local stress distributions may be important. Additional replicated testing and a confirmatory experiment are required to distinguish real parameter effects from specimen-to-specimen variability.

VI. CONSTRAINTS

There are several limitations that should be addressed before submission of this manuscript to a journal. First, in the source the tabulated response is alternately referred to as breaking strength and as von Mises stress, and these quantities need to be separated and correctly labelled. Second, the adhesive product designation, mixture-ratio convention, curing conditions, and bond-line measurement procedure should be validated. Third, the report lacks raw force-displacement curves, number of replicates, standard deviations, confidence intervals, and a complete mesh-independence study. Fourth, there is only one reported response for each combination of the L9 array, therefore statistical significance and interaction effects cannot be robustly assessed. Finally, the comparison of the riveted and adhesive joints explicitly has to record the same loading and boundary conditions.

VII. Conclusion

In this study, a scarf adhesive joint subjected to tensile loading was evaluated using Taguchi L9 design, analytical calculations, FEA and experimental testing. The highest response within the nine-run array was 2.3808 N/mm² for a 60° scarf angle, 1.0 mm adhesive-layer thickness and 1:1 resin-to-hardener ratio, according to the provided report. The source also reported close agreement between analytical, FEA, and experimental equivalent-stress values for the adhesive joint, 2.29 MPa, 2.38 MPa, and 2.34 MPa, respectively. The results support the usefulness of a combination of numerical analysis and physical testing in the study of bonded joint design. The riveted-joint values reported by the source were higher than the adhesive joint values in the cited comparison, but this is configuration specific, and must be confirmed that the compared cases are under consistent conditions. The initial study identified scarf angle as the dominant factor but further replicated testing and formal statistical analysis is required to determine the magnitude and significance of each factor. Response definitions, units, adhesive specification, and model assumptions must be reconciled with the original laboratory records prior to publication. Future work should involve repeat tests, mesh convergence analysis, a confirmation experiment, control of surface preparation, environmental durability testing, and validation with dissimilar adherends.

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